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Drill bits for frozen fine-grained soils

Paul V. Sellmann and Malcolm Mellor

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20. Abstract (cont'd).

problems than similar materials at somewhat lower temperatures because of different fracture and transport characteristics. Our approach has been to work toward optimum efficiency, with special emphasis on reducing thrust and torque requirements for light-weight drills.

Important features of drills that perform well in frozen fine-grained materials include: (1) full face cutting, (2) a pilot bit that can cut and clear its cuttings, (3) appropriate cutter angles (adequate clearance angles and positive rake), (4) sharp but durable cutters, (5) unobstructed flow paths for chip clearing, and (6) stabilizing features for smooth running.

Examples of successful bits are discussed and illustrated. Some were built or modified at CRREL, while others are of commercial manufacture. *Keywords: ->(to joi)*

PREFACE

This report was prepared by Paul V. Sellmann, Geologist, Geophysical Research Branch, Experimental Engineering Division, and Dr. Malcolm Mellor, Research Physical Scientist, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. The review was performed as part of DA Project 4A762730AT42, Design, Construction and Operations Technology for Cold Regions, Task Area CS, Combat Support, Work Unit 035, Drilling Technology for Cold Regions.

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DRILL BITS FOR FROZEN FINE-GRAINED SOILS

Paul V. Sellmann and Malcolm Mellor

Introduction

In drilling and core-sampling operations, frozen soils behave differently from unfrozen soils and common rocks. Drilling equipment that performs well in unfrozen material is sometimes very disappointing in frozen ground, even with application of brute force.

Frozen fine-grained soils, typically silts and clays with high ice content, display properties that are distinctly different from those of unfrozen ground; they are also different from other frozen materials such as sand, gravel and rock. Relatively warm ice-saturated fine-grained soils that are only a few degrees below freezing contain some unfrozen water at the grain boundaries. Compared to rocks, these soils are not particularly strong, but they are ductile and tough and have to be cut more like a metal or plastic. Colder fine-grained soils (below -5°C) have lower unfrozen water content and slightly different properties; they are stronger and tend to be more brittle (Anderson and Morgenstern 1973, Ogata et al. 1983). However, they still have less strength than most chemically cemented rocks or crystalline rocks, which have more tendency to crack and crumble under the action of a drill bit. The properties of fine-grained soils generally differ from those of frozen granular soils because the fine soils have higher unfrozen water content. Furthermore, these soils commonly have higher ice content, which contributes to their lower strength. They are also inherently less abrasive, since the bit is working on mineral particles that are very small compared to cutter size. The mineral particles are also often suspended in an ice matrix, which makes cutting of the ice-rich fine-grained soils more like ice drilling. Drilling in these soils is usually very smooth and vibration-free, with little impact loading on the cutters.

One consequence of the properties of the "warm" frozen fine-grained soils is that percussive drills and roller rock bits are far from ideal.

They are often completely ineffective, since they are better suited for use in brittle material. Another consequence is that rotary drag bits which do not cut over the whole face are unlikely to perform well in fine-grained frozen soil, since there is virtually no overbreak. Finally, there is a potential for problems with the cuttings, or chips, which can easily adhere and compact on the bit, in the transport system, and on the hole wall, especially when subjected to pressure, or when exposed to higher temperatures or moisture.

This report is based on our experience with construction of drilling and sampling tools for use in frozen ground; it treats only one aspect of the problem, drill bits for frozen fine-grained soil. Our approach to construction of drilling tools was influenced by the need to obtain undisturbed cores and to produce holes with small equipment with limited thrust and torque. Very efficient systems are needed to meet these requirements. Application of excessive thrust and torque cannot compensate for inappropriate drilling tools and it usually produces poor quality cores, disappointing drilling rates, and excessive wear on the equipment.

Experimental and theoretical studies at CRREL have provided insight into why some bits are unsuccessful in frozen soils. They have also laid the foundation for systematic design of efficient bits and cutters. This report covers both auger drills and systems that use fluid circulation, including solid stem augers, hollow stem augers, simple coring tools, double-wall core barrels, and casing bits. It also describes some commercial tools that have been used successfully with little or no modification.

Characteristics of soils

Drilling in frozen soil is more akin to drilling in rock than in unfrozen soil. When the pores and voids in the soil are more or less filled with ice, the material has significant tensile strength and relatively high strength in shear and compression, and it cannot be compressed or compacted by moderate pressures.

For drilling purposes, it is convenient to classify frozen soils broadly on the basis of grain size. Fine-grained soils include various mixtures of silt, clay, organic material and ice. They are found both on land and underwater. Fine-grained frozen soils are most commonly cut by small drag cutters that work by a chisel action. Coarse-grained frozen soils consist primarily of sand and gravel, with aggregates ranging from small pebbles to

big cobbles. These soils have properties much like concrete. This creates problems, since the rock fragments can be bigger than typical drag cutters, so that some cutters, or even the entire bit, are at times effectively working in solid rock. Tool wear is much greater in coarse-grained material because of its greater strength and more abrasive nature, and because non-uniformity causes impact loading. In frozen gravel or frozen till, chisel-type drag cutters only work well if the drill bit and its cutters are very big. For drills of fairly small diameter, suitably designed drag bits work consistently well in frozen silt, frozen clay and frozen organic soils. In frozen sand, cutting is less easy and tool wear is more rapid, with small cutters reaching a practical limit in coarse-grained frozen sand.

With high ice content and temperatures only a few degrees below freezing, frozen clay and frozen silt tend to cut cleanly under the action of a chisel-type cutting tool, with little overbreak. In this respect they behave something like metals under the action of machine tools.

Rocks are often brittle and friable, and when they are attacked by widely spaced clawlike cutters the material between the cutters tends to break and crumble. By contrast, when ductile frozen soils are attacked by similar arrays of widely spaced cutters, the cutters dig furrows but do not necessarily break out the material between the claws. Thus, in fine-grained frozen soils, to ensure proper performance under all ground conditions and temperatures, drill bits have to cut the entire area that is to be penetrated.

Rotary drilling with drag cutters

In this report the terms drag-cutter and drag-bit are used to refer to any cutting tooth, or combination of cutting teeth, that works by a chisel action, with tools traveling tangentially or approximately parallel to the surface of the material that is being cut. An example of a simple two-cutter bit intended for use with a circulation fluid is shown in Figure 1. Drag cutters are typically chisel-edge wedges or pointed bullet-shaped claws (Fig. 2). Diamond bits are also essentially drag bits with small multiple cutters of irregular shape, but they are not considered here since they are not well-suited for use in frozen fine-grained soil.

A drag-type bit makes a hole simply by rotating a head, or bit, which is fitted with blades or teeth. In an auger system, cuttings are either

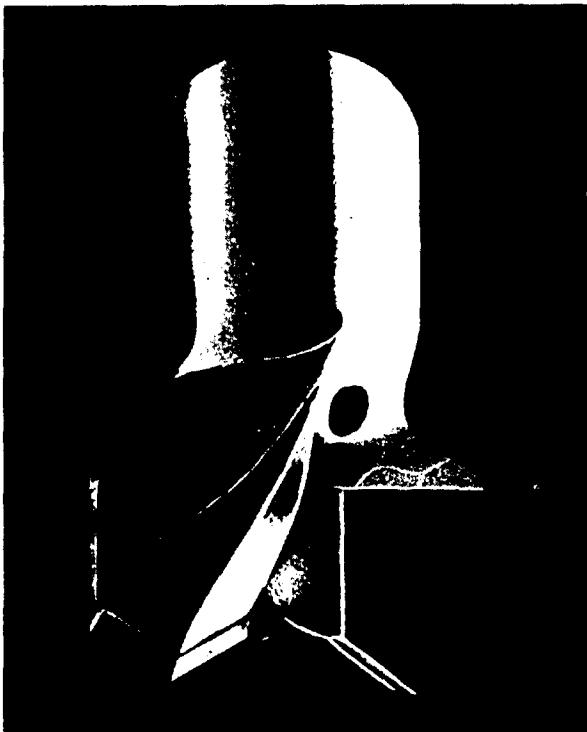
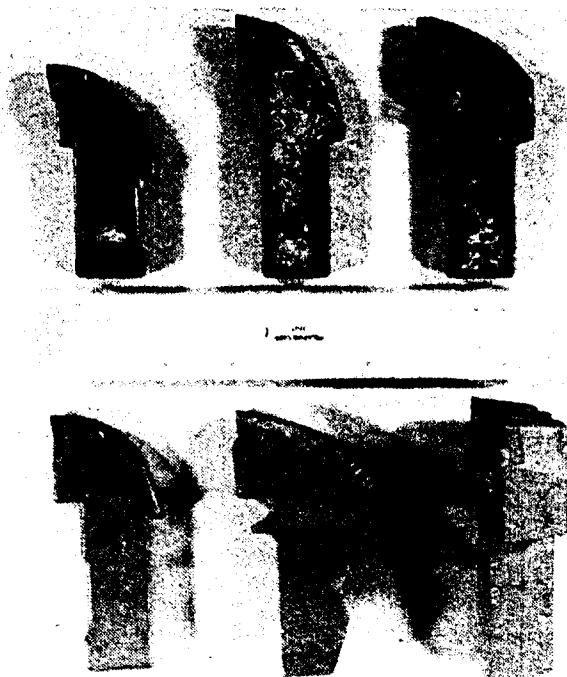
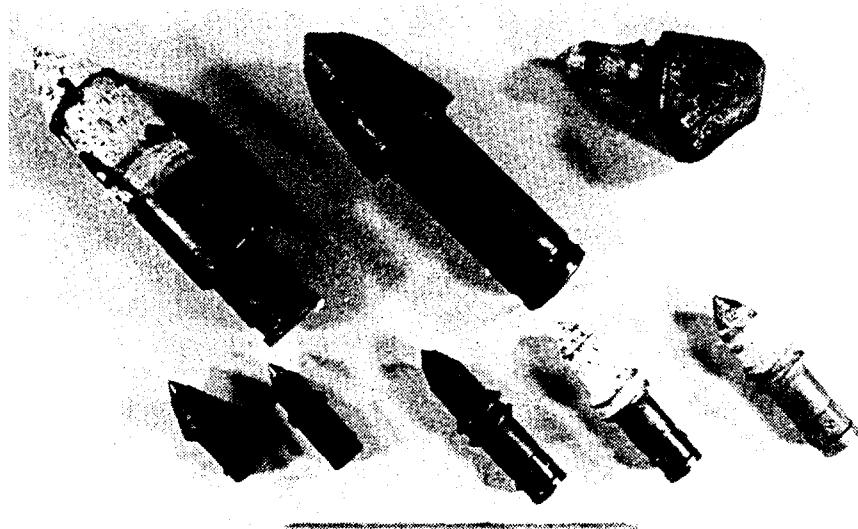


Figure 1. Small diameter drag bit with two cutters. This simple design has characteristics that make it well suited for use in frozen fine-grained soil. (Photo courtesy of Ugine Carbone, Grenoble, France.)

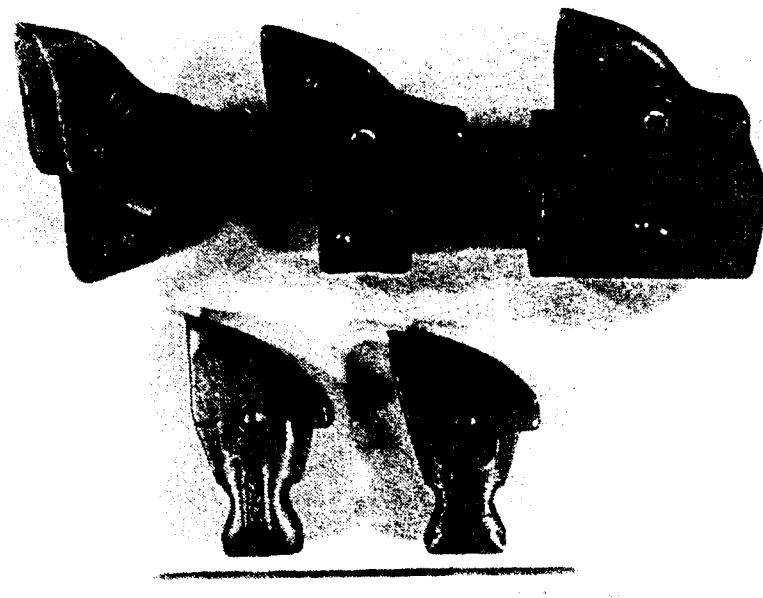


a. Small picks for mining machines, all tipped with tungsten carbide inserts.

Figure 2. Examples of parallel-motion tools for cutting rock and other brittle materials. These are potentially applicable to drilling in frozen fine-grained soils (from Mellor 1977).

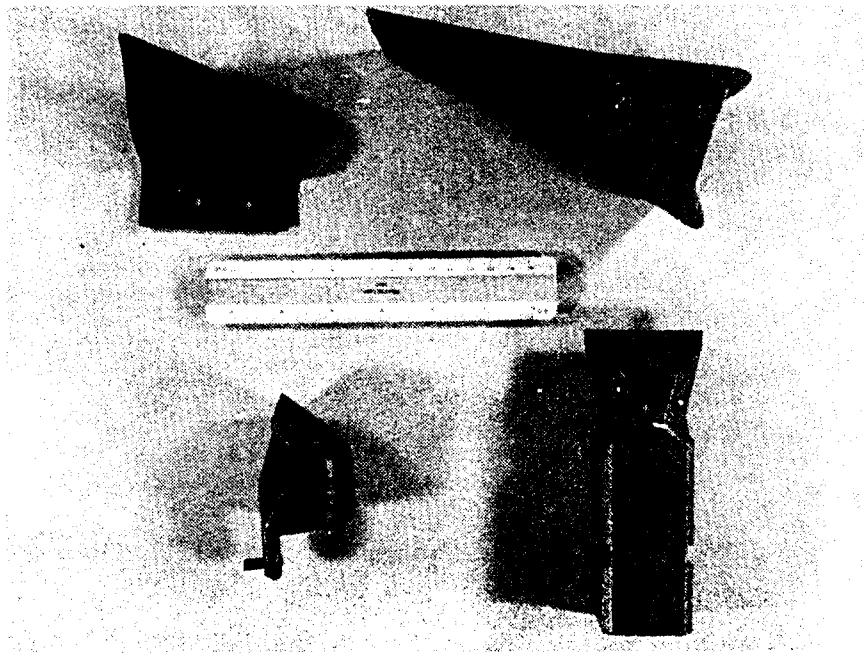


b. Rotationally symmetrical tools known variously as "bullet bits," "plumb-bob bits," "pencil bits," "conical bits," or "point attack bits." The tungsten carbide insert is set in a similar manner to the lead of a pencil.

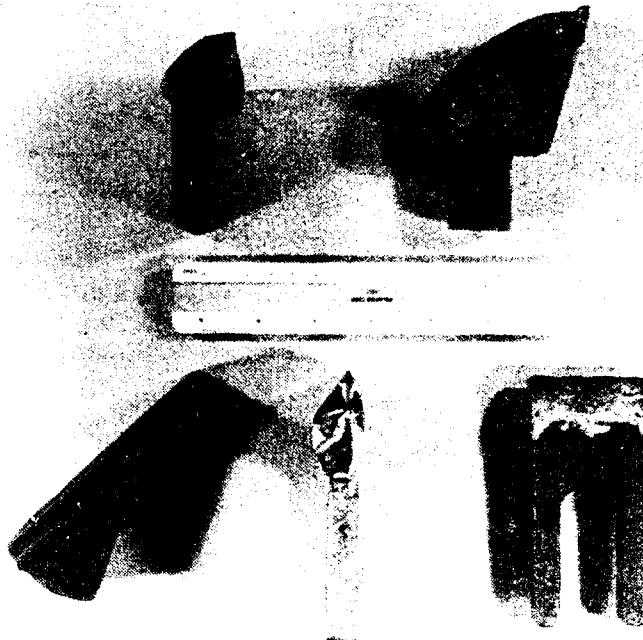


c. Medium size "parrot beak" picks for mining and rock-cutting machines.

Figure 2 (cont'd).



d. Clockwise from upper left: small hard-faced blade for a ladder-type soil trencher; large tooth for use on heavy auger drills, bucket wheel trenchers or excavator buckets; heavy pick for tunneling machines; hollow rock-cutting pick for "spigot" mounting.



e. Teeth for heavy augers that drill in soils and weak rocks.

Figure 2 (cont'd). Examples of parallel-motion tools for cutting rock and other brittle materials. These are potentially applicable to drilling in frozen fine-grained soils (from Mellor 1977).

transported to the surface by a continuous flight auger (helical scroll), or removed by repeatedly lifting cuttings to the surface while they are held: (1) on the flights of a short section of auger, or (2) in a cylindrical bucket. In a drill system with fluid circulation, chips are carried to the surface by a stream of air or liquid which circulates down the drill stem and up the annulus, or the other way around (reverse circulation). Holes produced by drag bits cover a very wide size range, from about 1 in. (25 mm) in diameter to 10 ft (3 m) or more (Fig. 3).

The basic rotary coring drill has a hollow tube, or barrel, to pick up and confine uncut cylindrical samples of rock or soil. Attached to the end of the core barrel is an annular cutting ring, or shoe, which produces the core that feeds into the barrel as the drill penetrates. The core is often retained by a mechanical device called a core catcher. Cuttings from the process may be removed by a fluid circulation system, or they may be transported a short distance by auger flights for storage in or above the core barrel. The length of a single coring run is limited by the length of the core barrel, typically in the range 2 to 20 ft (0.6 to 6 m). At the end of each coring run, the core barrel is lifted to the surface for removal of core, and perhaps cuttings. This usually involves laborious uncoupling and recoupling of the drill stem sections. However, downhole systems have been constructed with drive, thrust and torque reaction at the barrel, so that the drill can be reeled to the surface by a flexible cable or umbilical.

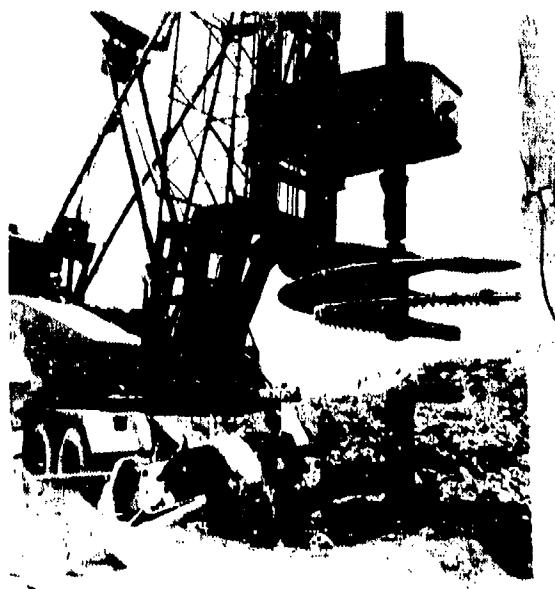


Figure 3. Large diameter auger drill attachment, mounted on a crane. This drill head has a diameter of 10 ft (3 m).

In shallow coring, or for core sampling in unstable ground, operations are greatly simplified by the use of a hollow stem auger. This system is a continuous-flight auger with a large diameter open stem. Inside the hollow auger another drill stem is placed, and this can carry either a solid pilot bit for drilling the hole center, or a core barrel that can be rotated or driven for sampling purposes. After penetrating for an interval by turning both the auger and the pilot bit, the inner stem and pilot bit can be retrieved and a core barrel can be fitted. The auger stays in the hole to act as a casing until the hole needs to be advanced for the next sample run.

There are many ingenious variations on basic drill systems, but these examples serve to illustrate some types of equipment that can utilize drag bits as part of the drilling process.

General characteristics of drag bit boring heads

Although there are various types of cutting teeth for rotary drag bits, chisel-edge teeth or blades are best suited for fine-grained frozen soils, particularly on small diameter bits. It is much easier to place blades or chisel-edge cutters on small bits to ensure full face cutting and smooth flow of chips. Cutting tool angles on blade cutters can also be adjusted to reduce the thrust required for small hand-held drills. The cutting teeth have to be distributed on the cutting head, or bit, so that there is adequate coverage of the advancing face of the hole. In ductile frozen soils, almost 100% of the face has to be contacted directly by cutting teeth, since there is much less overbreak than in friable rocks.

Any rib or boss of uncut material becomes a bearing surface that can only be rubbed away by abrasion or frictional melting. In principle, 100% cutting coverage can be achieved by a single blade extending along one radius. In practice, it is better to have discrete teeth distributed in such a way that each tooth can exploit free surfaces created by its neighbors, while distributing the cutting forces circumferentially so as to minimize vibrations. This can be achieved with two or more radial wings, each carrying teeth that are slightly offset from the groove cut by the preceding cutters. Other possibilities are to arrange teeth in helical arrays, over conical surfaces, or in some other three-dimensional pattern.

As the drill bit rotates and penetrates axially, each point on the bit follows a helical penetration path. This helical path becomes progressive-

ly steeper as the radius from the hole center decreases, until the helix angle is 90° at the center of the bit. Because each cutting tooth is a chisel that has to be held at a certain angle to the advancing surface, cutters on bits designed for rapid penetration should be set at progressively steeper angles as the center of the bit is approached. Near the center of the hole, it is impossible to cut effectively when penetration rate is high relative to rotation speed, since the penetration path has to be very steep. For this reason, special provisions have to be made. One possibility is to use a pilot bit with smaller teeth, thus reducing the scale of the problem zone. Another possibility is to not cut the center and leave a small uncut core which will break off when its length/diameter ratio becomes large enough. Yet another possibility is a sharp "spear-point" that indents and reams the center.

The cutting performance of a tooth depends on the sharpness of the edge, but there are limits to the sharpness that can be maintained when cutting earth materials. Cutters usually have an edge of tungsten carbide, with the grade of carbide chosen to give an optimum balance of abrasion resistance and impact resistance. For high efficiency, cutters have to be kept sharp by replacement and by regrinding. Tungsten carbide inserts should be set into properly oriented milled pockets in the bit. The steel supports or backs the relatively brittle carbide, which is oriented or attached so that the resultant cutting force cannot apply flexure to the insert teeth. When custom bits are fabricated in a machine shop, some care is needed in silver-soldering the carbides to the body of the bit; even slight contamination of the surfaces can seriously weaken the solder joint. On very big drills, the teeth may be steel forgings, some with hard-facing on the edges (similar to the cutter in the upper right of Fig. 2d). Teeth of this kind are usually very blunt, leading to high cutting forces and higher power consumption. Large drills can also utilize massive carbide cutters that are clamped mechanically to a bit. These cutters are often multifaced, allowing them to be rotated periodically to present new cutting surfaces (Fig. 4). Carbide cutters perform well and hold their edges in frozen fine-grained material, which is the least abrasive of the frozen soils.

The cuttings produced by the teeth have to be cleared away from the work face and transported up the hole, either by fluid circulation or by

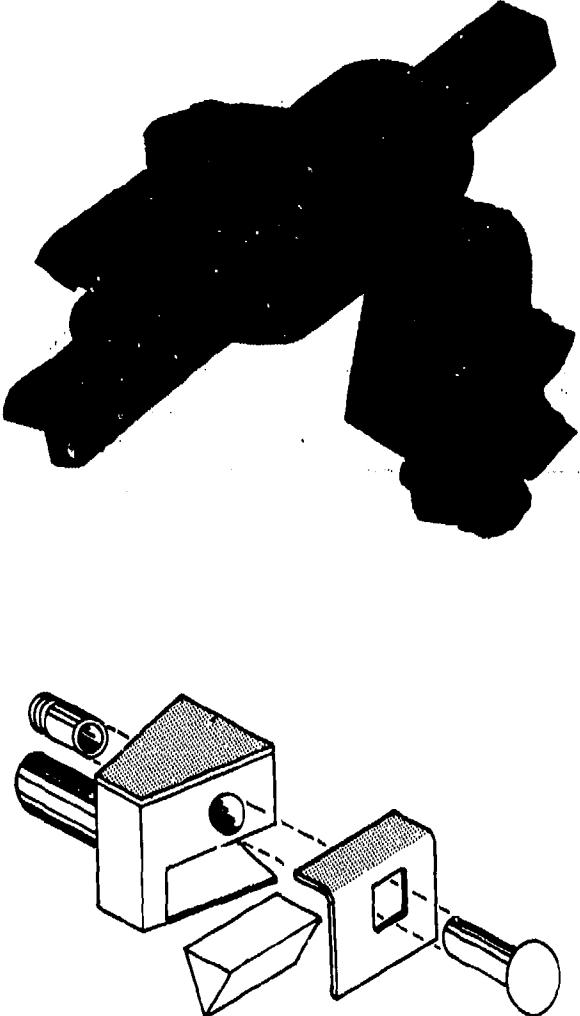


Figure 4. Most tungsten carbide cutters are silver-soldered to bits. However, one auger (made by Alaskaug) commonly used in frozen ground has triangular carbides that are locked mechanically onto the bit assembly. This figure illustrates the cutter assembly and one of these augers. (Photo courtesy of Alaskaug, Cincinnati, Ohio.)

screw (auger) conveyance. The bit has to be designed to provide smooth open paths for the chips to travel away from the cutting edges. If the clearing paths are obstructed or constricted, cuttings may clog up and become jammed into coherent masses. This can completely defeat the drill. This problem seems to be greatest in warm fine-grained material that is just below the freezing point.

Cutter angles

The shape of a cutter and the orientation relative to the work surface determine the cutting efficiency, especially in frozen fine-grained soils. Although tool shapes vary considerably (Fig. 5), in this discussion the emphasis is on chisel-edge tools, in which the tool cross section is a sharp wedge. These tools are often used for orthogonal cutting, with the cutting edge at right angles to the tangential travel direction (Fig. 6). However, on some drill bits cutters are set for oblique cutting to aid lateral transport of material. The main concern is usually with the angle of the wedge, and the angles that determine its orientation.

The definitions of tool angles for a chisel-edge cutting orthogonally are illustrated in Figure 7. The included angle of the wedge describes its overall sharpness. The rake angle is the slope of the front face of the advancing wedge, measured from the normal. The relief angle is the slope of the underside of the tool. However, rake and relief angles can be

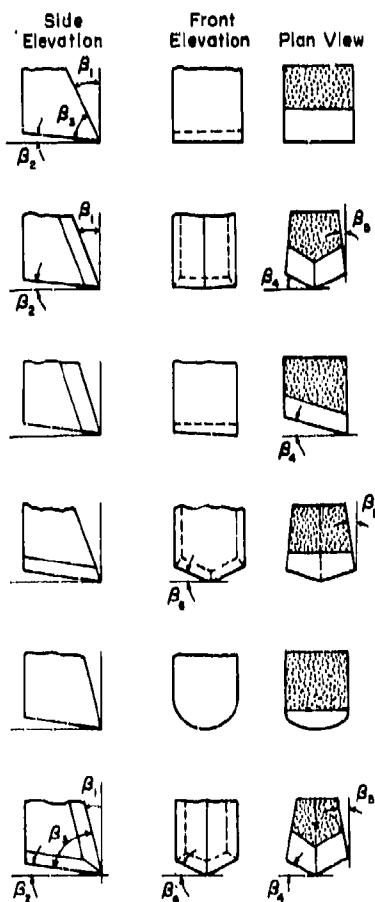
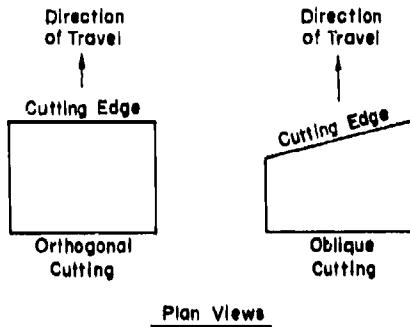


Figure 5. Examples of cutters with various configurations, with designations of tool angles (from Mellor 1977).



Plan Views

Figure 6. Orthogonal cutting and oblique cutting (from Mellor 1977).

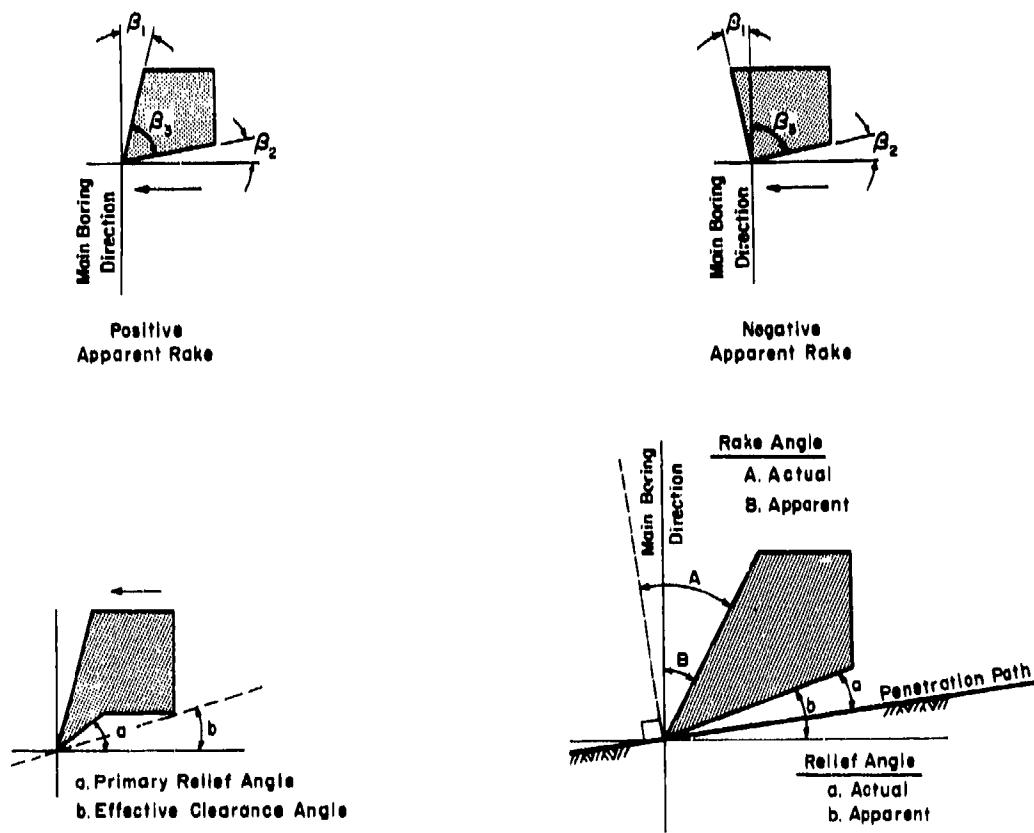


Figure 7. Tool angles for drag bits on rotary boring heads (from Mellor 1976).

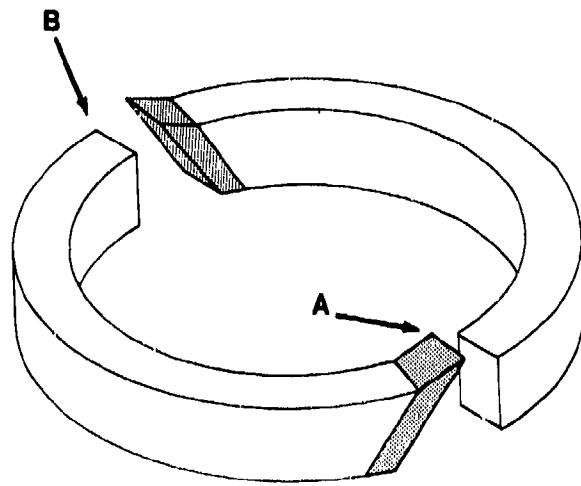
defined in two ways. When defined with reference to the axis of the drill, the rake and relief angles can be termed apparent values, i.e. the values when axial penetration rate tends to zero. The actual rake and relief angles are defined with reference to the helical penetration path, the slope of which varies with axial penetration rate, rotation speed, and radius on the boring head. Apparent angles are constants, whereas actual angles vary with the operating conditions, thus influencing the cutting efficiency.

The relief angle is probably the most important angle. If the apparent relief angle is zero, the drill cannot penetrate. When the apparent relief angle is finite and positive, the penetration rate reaches a limit when the helix angle of the penetration path equals the apparent relief angle, i.e. when the actual relief angle is reduced to zero. Given specifications for rotation speed and penetration rate, the minimum value of apparent relief angle can be calculated for any position on the boring head. Alternatively, for any given bit, a maximum penetration rate can be calculated for any specified rotation speed.

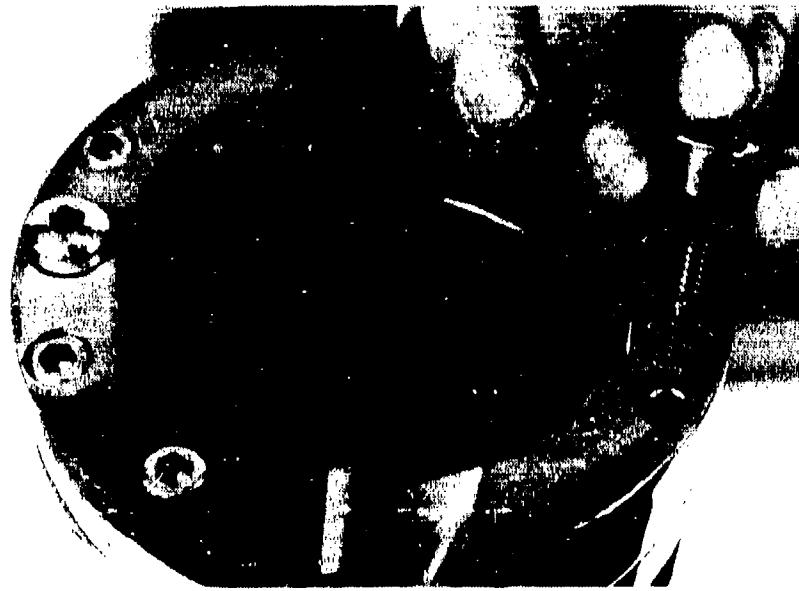
In considering relief angles it is important to distinguish between the primary relief angle and the effective relief (or clearance) angle (Fig. 7). The primary relief angle is determined by the geometry of the tool and its setting. The effective relief angle, or clearance angle, can be smaller than the primary relief angle if some trailing part of the bit body can rub on uncut material before the helix angle of the penetration path reaches a value equal to the primary relief angle, as would be the case on the two-cutter coring ring shown in Figure 8.

The rake angle is also important since cutting becomes easier as positive rake increases. Negative rake increases thrust and torque requirements. However, in some cases there are few options over the rake angle. With the relief angle decided and the included angle fixed, the rake angle is determined automatically. In principle, when the other angles are considered, it is possible to have too great a positive rake, as will be seen from the following notes.

The included angle determines the overall sharpness of the tool, and by that token it should be small. However, it is not useful to make the included angle so small that the tool becomes a knife edge. The wedge angle has to be big enough to resist breakage by flexure, to minimize



a. Diagram of a simple coring ring with two bits which illustrates the influence of total cutting ring geometry on relief angles. The relief angle of the individual cutters has little bearing on the relief angle for the cutting shoe overall. The effective clearance is the much smaller angle from the cutter tip (A) to the trailing edge of the cutting ring in front of the next cutter (B) (from Mellor 1976).



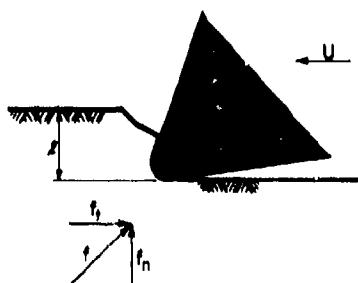
b. A cutting shoe on the CRREL coring auger. This tool is commonly used in frozen silt and fine sand when fitted with carbide cutters (Mellor and Sellmann 1975). This version takes a 3-in. (76-mm)-diameter core, while other models take cores as small as 1 in. (25 mm) in diameter. The primary relief angle of the cutter is 20° compared to an effective clearance angle of 1.5° . This allows a maximum penetration of 0.3 in. (7.6 mm) per revolution.

Figure 8. A simple two-cutter bit shoe and the CRREL coring auger cutting shoe.

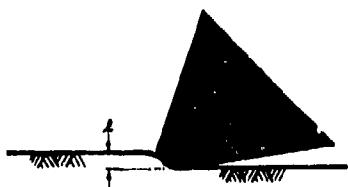
chipping on its edge, and to hold a sharp cutting edge. For work in hard materials, $30^\circ - 40^\circ$ might be about the practical minimum. Some earth-moving machines have large teeth with rake and relief faces almost parallel, but they have a blunt tip; this facilitates deep penetration in soft material, but they are not efficient rock cutters.

While the included angle has a strong effect on the penetration resistance for a cutter, the stress concentration at the cutting edge depends also on the tip radius (Fig. 9). When the bit is operating in such a way that the chipping depth of the cutter is small (rotation speed high relative to penetration rate), the cutting efficiency depends almost entirely on the tip radius ("sharpness") of the tool (Fig. 9b).

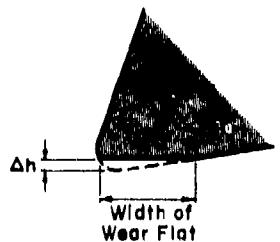
When bits are operated so as to achieve penetration rates that are low in relation to rotation speed (small penetration per revolution), the helical penetration paths are much flatter than the tool relief angles.



a. Deep cutting, in which the chipping depth l is significantly greater than the radius of the tool tip r . Force components f (resultant), f_n (normal) and f_t (tangential) are illustrated.



b. Shallow cutting, in which the chipping depth l is comparable to, or smaller than, the radius of the tool tip, making the rake angle largely irrelevant.



c. Wear flat on the relief face (flank wear). Note that the wear flat is not always exactly parallel to the tangential direction; it sometimes inclines slightly, giving an initial negative relief angle of a few degrees.

Figure 9. Cutter terminology (from Mellor 1977).

This eventually produces a "wear flat" behind the cutting edge of the tool (Fig. 9c). Once a wear flat of this kind has been ground on the relief surface of the tool, it becomes more difficult to operate the bit in accordance with its design characteristics, since it no longer has an adequate primary relief angle. In fact, the wear flat can sometimes give a slight negative relief angle.

We have made simple tests that suggest a more straightforward way to determine rake and relief angles. When a hand chisel is used to groove the surface of rock, concrete, frozen soil, ice, and suchlike materials, there is a definite angle of inclination which directs the resultant of the cutting forces along the axis of the chisel. At shallower angles of inclination the chisel rides up out of the work unless a high moment is applied. At steeper angles the chisel digs in too deeply and does not travel parallel to the surface. For frozen silt, the optimum angle appears to be around 48° inclination from the work surface. Following this idea, the optimum angle of the tool's bisector is first decided; the relief angle is this inclination minus the half-angle of the wedge, and the rake angle is the complement of the inclination minus the half-angle of the wedge.

Flow paths for chip clearing

Frozen soil cuttings tend to stick together and occasionally freeze together, particularly in silt- and clay-rich soil. This tendency is accentuated when chips are packed close together, when frozen materials are only slightly below freezing, and when tools or circulation fluids are warm. To avoid accumulation and jamming of chips in a drill bit, there has to be smooth and unimpeded flow of chips from the cutting edge to the pickup point for the transport mechanism. If flow paths are constricted or obstructed, or if the bit produces chips faster than it can transport them away, blockages will develop. Blockages can grow until the entire bit is clogged with tightly packed cuttings. The cutting head then becomes a smooth blob that is incapable of further penetration, even when driven by very large drilling rigs. Packing of cuttings between the auger flights and the hole wall can cause the drill string to stick in the ground. When this is accompanied by freezing it can make removal of the drill string difficult to impossible.

Design deficiencies on bits and boring heads can include the following:

- (1) failure to provide clear transport paths from all cutting edges

- (2) inadequate cross-sectional area somewhere in the flow paths
- (3) abrupt turns in flow paths
- (4) steps or shoulders in flow paths
- (5) obstacles such as bolts or locking lugs projecting into the flow path from the bit, stem or flight
- (6) helical paths that are too steep
- (7) inadequate flushing in fluid circulation systems (poor positioning, distribution and orientation of fluid ports)

Careful design is particularly important for auger drills, which have to rely entirely on "shoveling" and screw transport (Mellor 1981), with the same rotation speed for the cutting and clearing functions. Some problems are easy to identify on the basis of common sense and physical intuition, but impressions and deductions can be checked by testing in a sticky material, such as moist unfrozen clayey silt. Debris accumulates in front of, or in the lee of, definite obstacles. If the bit is painted and then run in more abrasive material (sandy silt), paint tends to rub off in tight spots and other problem areas.

Flow path requirements can be analyzed to some extent, as can be seen from the following simple example.

If an auger bit is to avoid jamming, the clearing paths must be able to transport chips faster than the cutters can produce them, without totally filling the area between the flights (Mellor 1976). A full-face bit of diameter D , with axial penetration rate U , excavates material from the solid at a volumetric rate of $(\pi/4) D^2 U$. The chips occupy greater volume, and a bulking factor of 1.85 has been used when the chips are simply piled up and at rest. For an agitated mass of traveling cuttings, a bulking factor of 2 seems reasonable. Thus the volumetric flow rate for loose chips traveling through the bit is approximately $\pi D^2 U / 2$, which does not include spillback. For a coring auger, the corresponding production rate for cuttings is $\pi(D^2 - D_c^2)/4$, where D_c is the core diameter.

When auger flights are conveying near full capacity, the vertical speed of the cuttings, U_a , is approximately

$$U_a \approx \pi D f \tan \alpha \approx P f$$

where D is the outside diameter of the flight, α is its outside helix angle, P is the pitch, and f is the rotation speed. If the A is the hori-

zontal cross-sectional area of the annular space occupied by the flights, then jamming can be avoided by having

$$A \geq \frac{D}{2\tan\alpha} \cdot \frac{U}{f}$$

or

$$A \geq \frac{\pi D^2}{2 P} \cdot \frac{U}{f} .$$

The area A is

$$A = \frac{\pi}{4} (D^2 - d^2)$$

where d is the inner diameter of the flights (stem diameter).

U/f is the axial penetration per revolution; an increase in its value tends to increase the chance of jamming, but if U/f is too low, the cutters will not work properly. Within limits, an increase in the pitch of the flights, or an increase of α , will tend to lower the chances of jamming, but other problems arise if α is much above 30° . The condition for free flow of cuttings has to be met for all flow paths, and for all points on each flow path.

When fluid circulation is used, the processes of cutting and chip clearing are essentially independent and, in principle, chips can always be cleared fast enough to keep the bit free of cuttings. In practice, there are various factors that can reduce the effectiveness of the fluid stream, allowing local accumulation of chips. Potential problems include:

- (1) inadequate fluid velocity (insufficient flow rate for the size of bit and/or drill stem annulus)
- (2) poor location of discharge ports, leaving "dead zones" that are not swept by high velocity fluid
- (3) unsuitable orientation of discharge ports, giving inappropriate flow directions
- (4) constrictions or sharp bends in flow paths for the fluid/chip stream
- (5) warm circulation fluids that can heat bit surfaces and tend to melt ice-rich chips
- (6) ineffective cutting by the bit, leading to very small chips and excessive frictional heating (e.g. blunt cutters, or rotation speed too high for the prevailing penetration rate)

Keeping these things in mind, it is usually possible to diagnose problems and develop solutions. Expedient solutions might include such things as:

- (1) bigger pump or compressor
- (2) enlargement of discharge ports, drilling of extra ports and/or grinding of exit channels
- (3) grinding the bit to remove flow constrictions or smooth out direction changes
- (4) increasing fluid flow by reducing the number of required flow passages
- (5) cooling the circulation fluid, if necessary by heat exchange in winter or refrigeration in summer
- (6) producing relatively coarse chips by proper choice of bit, good maintenance of bit, and appropriate combination of rotation speed and penetration rate

Figure 10 shows an internal-discharge coring bit that was built for use with air circulation in fine-grained frozen soil. It was successful because its enlarged passages channel maximum flow across the entire cutting face. A similar bit with bottom discharge was unsuccessful, presumably because the small central ports did not give optimum streaming of the circulation fluid.

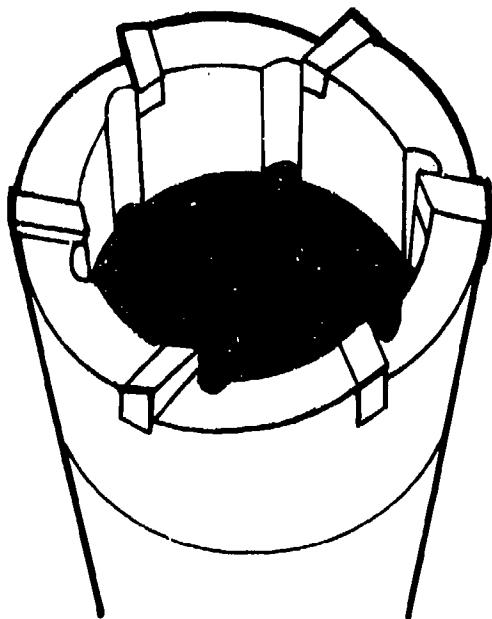


Figure 10. A saw-tooth bit with internal discharge made at CRREL. The bit has tungsten carbide tips. This combination proved successful in coring frozen sediment.

Field experience suggests that, when using compressed air, coring bits that have fewer cutters (5 to 6, compared with 8 to 10) are less likely to be blocked, at least at the flow rates available with typical equipment. With fewer cutters, chip size is increased for a given combination of rotation speed and penetration rate. The location of discharge ports on the bit is very critical if all cutter areas are to be flushed properly.

Stability in the hole

The stability and smooth running of a drill can be influenced by a number of factors, including symmetry of cutter placement, number of cutters, stability of the drive unit, and hole size compared to bit body diameter or auger diameter.

Stability problems are probably most noticeable on auger drills that are hand-held; the operator experiences excessive lateral shuddering motion with an unstable bit. Lateral motion tends to increase the hole size, since cutters are often set with some overhang and this permits scouring of the hole wall. There is then a tendency to produce a hole that cannot be contacted by stabilizing elements. If lateral motion occurs, it can usually be restricted by: (1) reducing external overhang of cutters, (2) balancing the forces by assuring that cutters have similar distribution and the same depth of cut on opposing wings*, (3) using bit designs that include pilots and step configurations, (4) providing bit shoulders for hole wall contact, (5) assuring hole wall contact by drill string stabilizers or auger flighting. If the shoulder area of a bit is increased to improve hole wall contact, it should not compromise cutting transport, since increased shoulder area can reduce the size of flow paths for cuttings.

Precise holes with little variation in diameter can be produced with auger drills. This can be achieved by machining all components of the drill bit and the auger flighting to the same diameter and allowing only slight overhang of the cutters. Precisely drilled holes are sometimes called for when small-diameter geotechnical devices have to be installed, usually at relatively shallow depth. In more routine drilling and sampling, a drill system with a uniform OD would cause some problems, since eventual wear of the cutter head would produce an undersized hole for the rest of the drill.

*Systematic procedures for balancing forces are discussed in Mellor (1976).

Examples of frozen ground bits and drills

Several drills have been modified and constructed at CRREL for use in frozen fine-grained soil. Most of these were for research and engineering applications, such as making shallow, small-diameter holes for instrumentation and for obtaining undisturbed core samples within 10 m of the ground surface. Others have been developed and utilized by drilling and engineering firms. Also, some commercial bits originally intended for use in soft rock and dense soil have been used with little or no modification.

These drills can be grouped into several categories on the basis of size and application, e.g. small-diameter drills, large-hole drills, coring augers (including hollow stem drills), and rotary coring tools (requiring circulation). Examples of some of these tools are illustrated in the Appendix.

Conclusions

The performance of drills intended for use in frozen fine-grained soil can be improved significantly by incorporation of some specific drill bit design features. Optimum design and efficiency of operation are extremely important when bits are to be used with drilling units that are hand-held, low-powered, or lightweight. These things are also important in coring operations, where minimum disturbance of the core is a requirement. Selection of an inappropriate or poorly designed bit can make penetration almost impossible, even with very large drills that have high torque and thrust capability. A bit that does not cut the material has to penetrate by abrasion and frictional melting.

The ductile nature of warm frozen silt requires that bits be constructed to cut the entire surface or face of the hole. This is necessary because very little overbreak occurs in these materials, and ribs of uncut material tend to prevent penetration by rubbing on non-cutting parts of the bit. Sharp but durable tungsten carbide cutters are necessary; they have to stay sharp as long as possible, and they have to resist damage from impact with any coarse-grained material encountered during drilling.

Bit clearance angles must be large enough to allow penetration at the maximum feasible design rates. Lack of adequate clearance angles is a common problem. Best performance is achieved when cutters have a positive rake angle. A step configuration is advantageous, since it improves cut-

ting efficiency and stabilizes the bit in the hole. Cuttings must be able to flow freely away from the bit in smooth, open flow paths that are free of obstructions.

Bits that successfully embody the above characteristics work well and can provide very impressive performance, even with lightweight drills that have limited torque and thrust, assuming adequate consideration has been given to transport of the cuttings away from the bit.

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APPENDIX A. EXAMPLES OF FROZEN GROUND BITS AND DRILLS

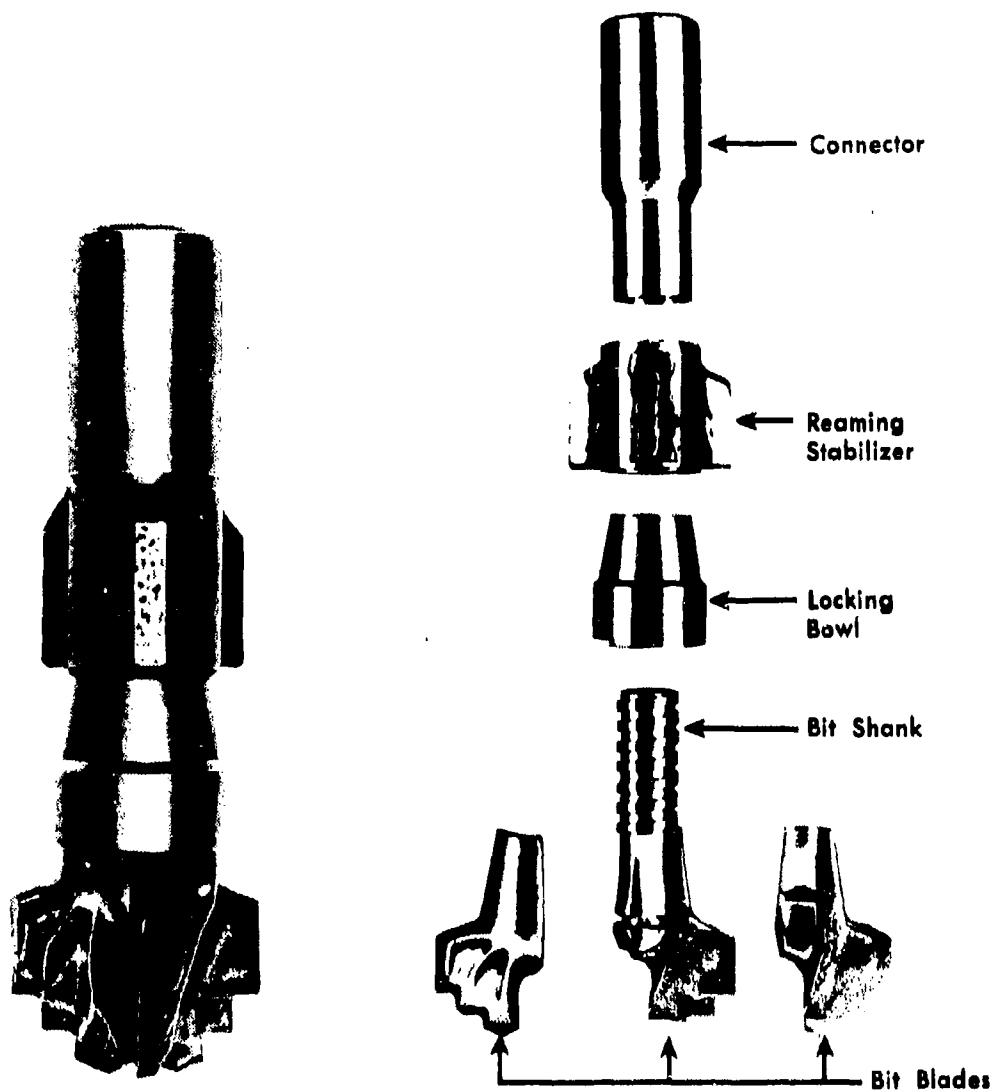


Figure A1. A commercial bit that has found direct application in frozen fine-grained soil is the old Hawthorne Blue Demon bit. This style of bit is now marketed by several companies. It has been used for many years in Alaska, including the period of early oil exploration on the North Slope, commonly with compressed air circulation for seismic shot-hole drilling in permafrost. It has replaceable blades that are hard-faced or armored with tungsten carbide cutting surfaces. The hard-faced bit has good self-sharpening characteristics and has been used in frozen fine-grained soils. These bits range in size from 1-7/8 in. (47.6 mm) to 16 in. (0.4 m). A bit of this type with carbide cutters used in ice-rich frozen silt near Fairbanks, Alaska, with chilled compressed air for circulation, produced 660 ft (200 m) of hole with little apparent reduction in performance. The last test hole, 60 ft (21 m) deep, was completed in a total of 20 minutes drilling time (Delaney, in press). (Illustrations courtesy of Hughes Tool Co., Houston, Texas.)



Figure A2. Two-wing auger intended for use on the Alaska pipeline project. It has large replaceable carbide-faced cutters similar to those in Figure 2e. This auger appears well suited for use in frozen fine-grained soils if the diameter of the pilot bit is great enough to allow cuttings to flow past the central auger shaft onto the flight without packing (see Sellmann and Mellor 1978).

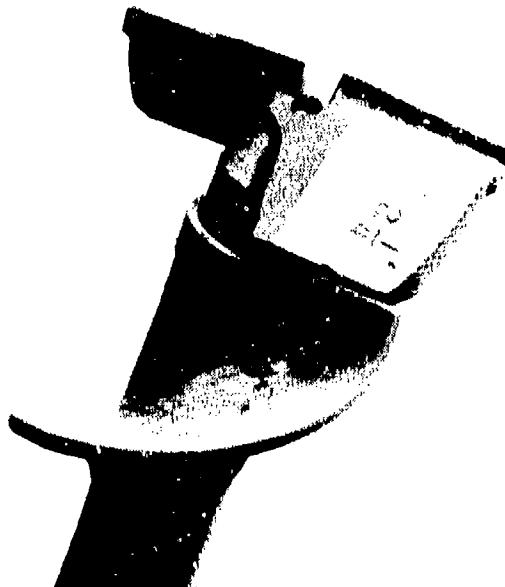


Figure A3. Small two-wing carbide-tipped auger drill. The flight used for this drill is from the standard CRREL ice thickness auger, which is normally fitted with mild steel cutters. Carbide bits were constructed to expand its capability to frozen fine-grained sediment. The carbide cutters were placed in pockets milled in the standard ice bit. Turned in frozen silt with a 650-rpm, 1/2-in. (13-mm) electric hand drill with a 10-amp rating, short-term drilling rates ranged from 81 to 138 in./min (2.1 to 3.5 m/min). At Prudhoe Bay, Alaska, 30 shallow 1-m-deep holes were drilled in frozen ground before the bit was dull enough to replace.

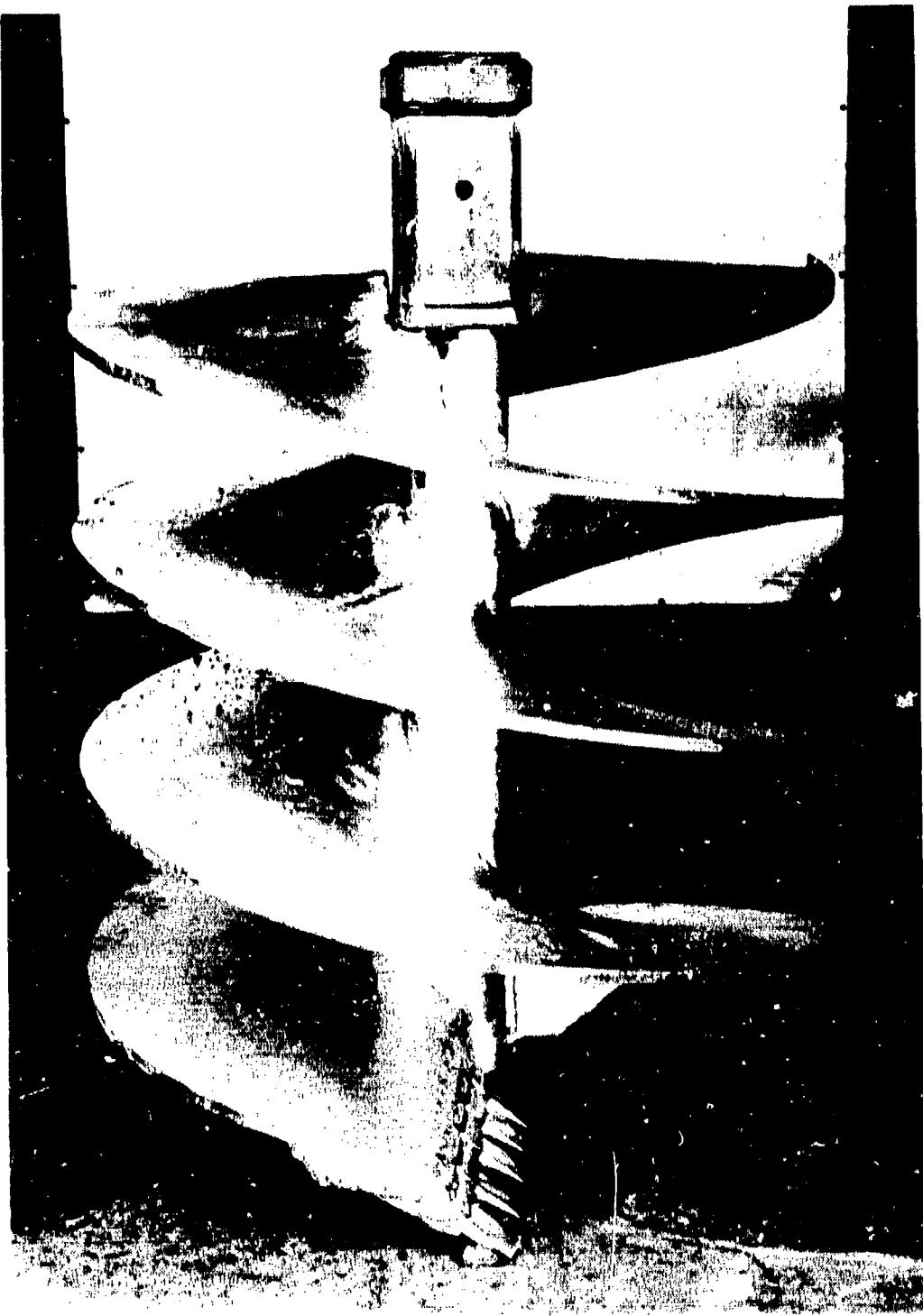
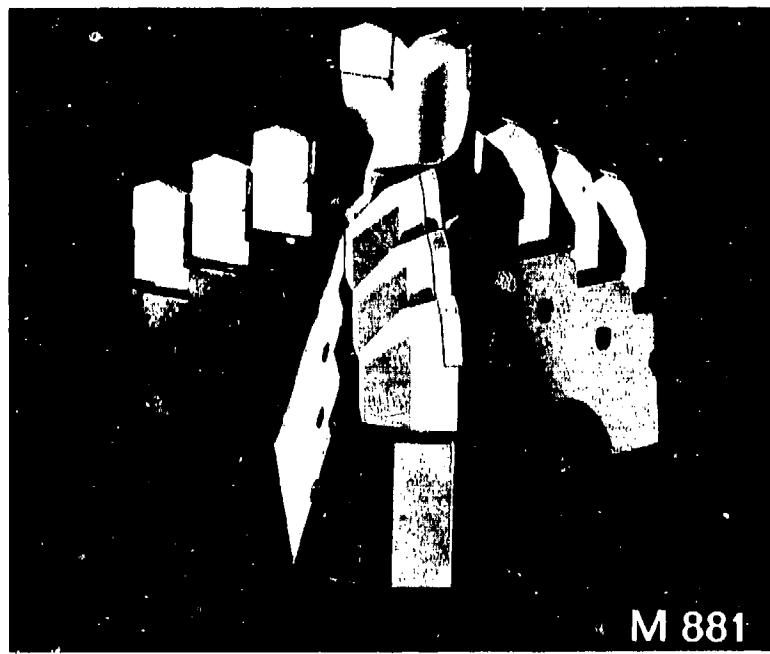


Figure A4. Large auger head for use in "soft ground" and weak rocks. The auger is fitted with large wedge style cutters similar to those shown in Figure 2d. (Photo courtesy of Calweld Division of Smith International Inc.)



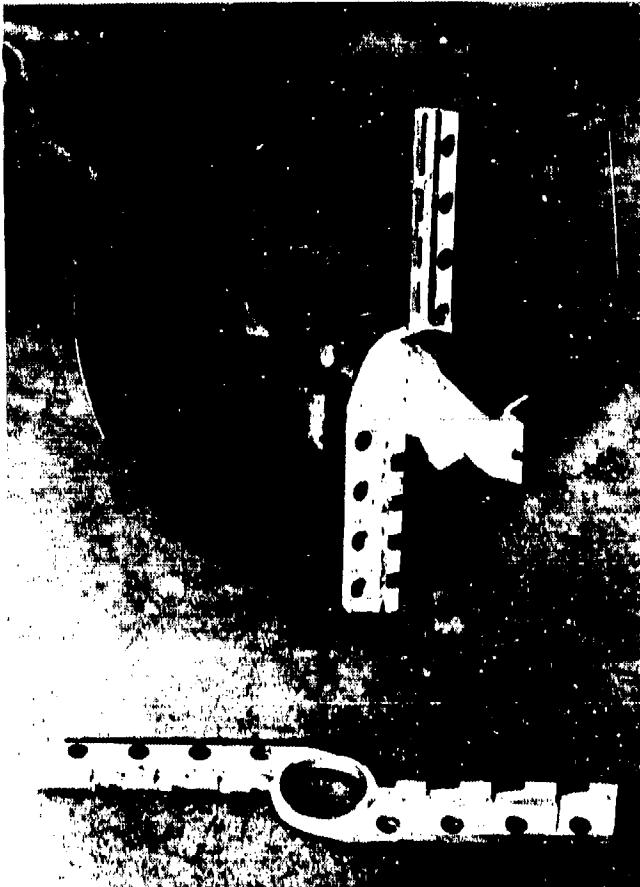
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Figure A5. A commercial auger bit that appears to have features that would make it suitable for drilling frozen fine-grained soil. We have not yet had an opportunity to evaluate this tool. (Photo courtesy of Ugine Carbone, Grenoble, France.)



a. A 14-in. (0.36-m) -diameter lightweight prototype auger constructed for making very shallow holes in frozen fine-grained soil with a hand-held drive unit. Holes of this size produced with hand-held equipment require a well designed drill. Maximum penetration rates achieved with this unit approached 6 in./min (15 cm/min).

Figure A6. Hand-held auger.



b. A more finished version of this large hand-held auger. This drill has a stepped pilot bit and staggered cutters on the wings.

Figure A6 (cont'd).

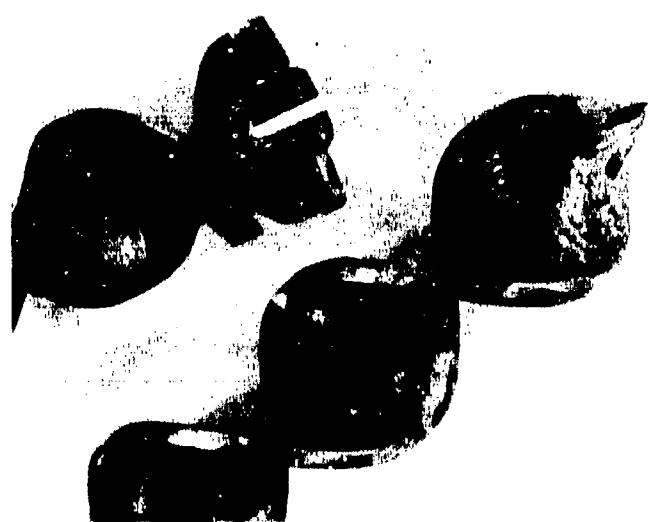
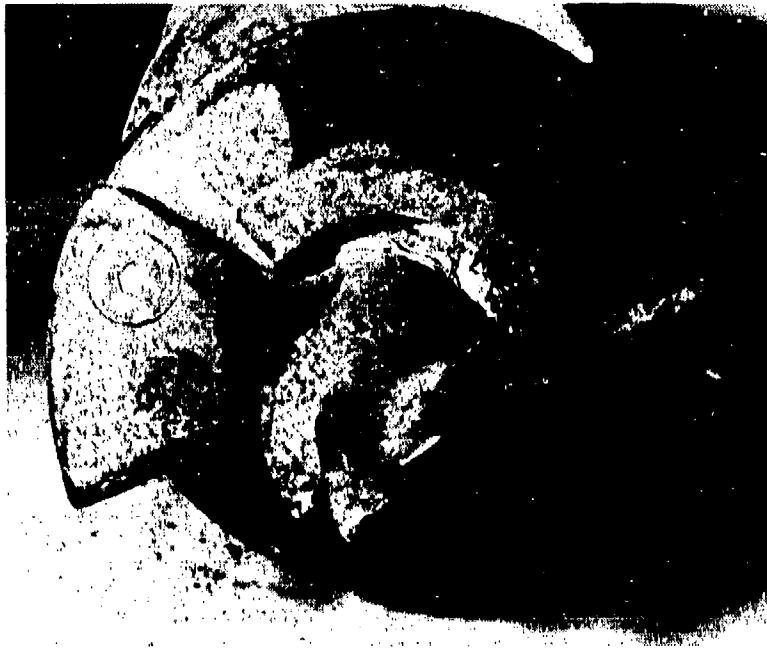


Figure A7. This 1.5-in. (38-mm) auger was made for drilling shallow holes for a variety of applications, including placement of instrumentation. When driven by the electric drill described in Figure A3, the auger produced the following results. No noticeable effort was required to counter the torque and no thrust was applied other than the weight of the drill, for an average short-term penetration rate of 10.6 ft/min (3.2 m/min). Two carbides were set on each wing of the auger. The inner cutters were set with zero rake and a 35° relief angle. The outer cutters had a positive rake of 13° and a 10° relief angle. The center of the hole was left uncut.



Figure A8. A modified 9.5-in. (241-mm)-diameter commercial/tungsten carbide pilot or full hole auger bit that worked well in frozen fine-grained soil with short-term penetration rates as high as 5 ft/min (1.5 m/min) (from Sellmann and Brockett, *in press*).

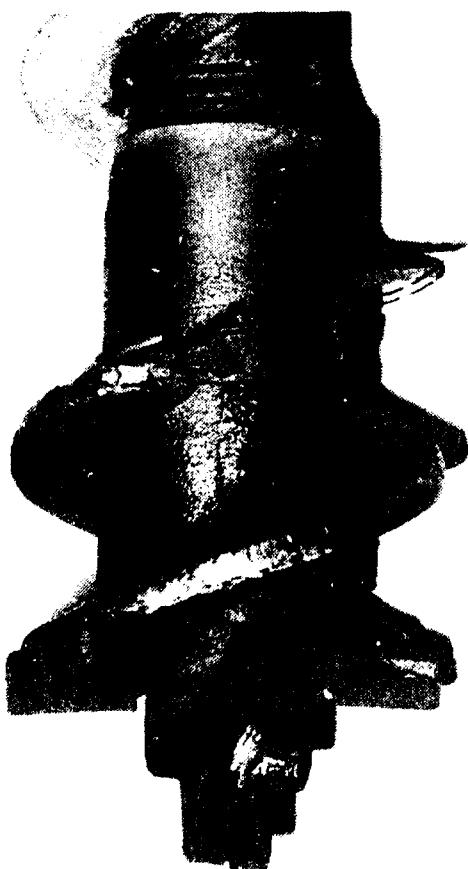


a. The blade-type cutter head of the Mobile Drill's 8-in. (0.2-m) hollow-stem auger, showing its flight cutters with carbide inserts. When sharpened, these perform well in frozen silt. The pilot is a modified version of Mobile's hard formation bit. This pilot is normally only available for their larger-ID hollow-stem augers. The pilot offered for this auger (Fig. A9b-1) was thought to be less than ideal because of the very large uncut center, and therefore a larger hard formation bit was modified for this 3-3/8-in.-ID auger. The unmodified pilot is shown in Figure A9b-3 and a modified version is shown for comparison in Figure A9b-4. The carbides were removed from the pilot bit and its diameter was reduced by turning it on a lathe. The cutters were then replaced and sharpened, and the bit body reshaped to increase the relief angles and smooth out the cutting flow paths. After modification of the flighting just above the cutter head (Fig. A9c) to prevent cutting build-up and packing, which stopped penetration, this new configuration allowed short-term penetration rates that ranged from 4.4 to 5.5 ft/min (1.3 to 1.7 m/min) in fine-grained permafrost.

Figure A9. Mobile drill.



b. Pilot bits for the Mobile hollow-stem auger shown in Figure A9a: (1) the pilot provided for this auger, (2) pilot made at CRREL, (3) hard formation pilot provided for the next-larger-ID hollow-stem, and (4) pilot modified from a bit like number (3).



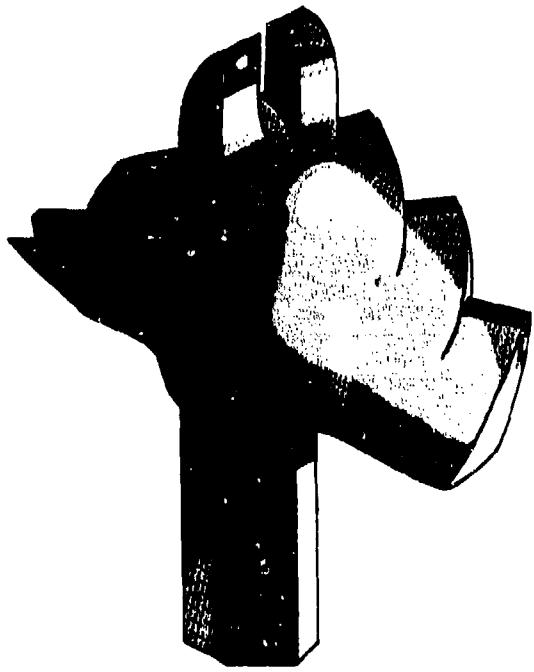
c. Segment of flight and rectangular housing (dashed) for a wedge-lock that was removed to improve cutting transport. In the original form, cuttings accumulated and compacted in this zone, blocking the bit and repeatedly stopping penetration after 0.2 m of drilling. Removal of the small segment of flight allowed the cuttings to move up and out of this congested zone between the double-start flight on the cutter head and the single-start flight of the auger. This was an expedient field modification. A better solution might be to shorten the flight on the cutter head that feeds up under the single auger flight.

Figure A9 (cont'd). Mobile drill.



a. Example of a commercial spear-style bit with a fishtail point, referred to by some as a clay bit. This bit used with a small auger rig was unable to penetrate frozen fine-grained soil. A core taken from the bottom of the hole (shown on the right) helps to illustrate part of the problem. The only part of this bit that might be capable of cutting is the fishtail segment with its carbide cutters, provided they are properly ground. The remainder of the bit is polished and caused melting of the hole bottom. Bright surfaces seen on the bottom of the top wing and in the bit center are bearing surfaces that contacted the frozen material and prevented penetration. The nub in the center of the core is one of the uncut surfaces. Material melted by contact of the spear segment with the hole bottom can be seen refrozen on the bottom of the bit. With this bit, application of maximum thrust from a small to moderate size drilling unit would only lift the machine off the ground without penetration. Bits of this type have been modified successfully for use in frozen ground. They are most easily converted into step bits with carbide cutters (Fig. A10b).

Figure A10. Bit examples.



b. Drawing of a step bit constructed from a fishtail style bit similar to the one shown in Figure A10a. This bit performed well in frozen fine-grained soil. It has the features considered necessary for work in this material; the step configuration provides lateral stability in the hole and for starting. Cutters on following steps also work on material with a free face. The bit also cuts full face except for the hole center, and the face is smooth and slopes back to meet the auger flights, allowing free cutting flow. The steps were made by turning the body in a lathe. The pockets for the carbide cutters and the open center were cut with a milling machine.

Figure A10 (cont'd). Bit examples.



Figure A11. Auger bit used for drilling frozen soil on construction projects in Siberia. The bit is approximately 0.4 m in diameter with wing cutters and spear point faced with tungsten carbide inserts. The cutters probably do not overlap, with uncut material removed by cutters on the following wing.

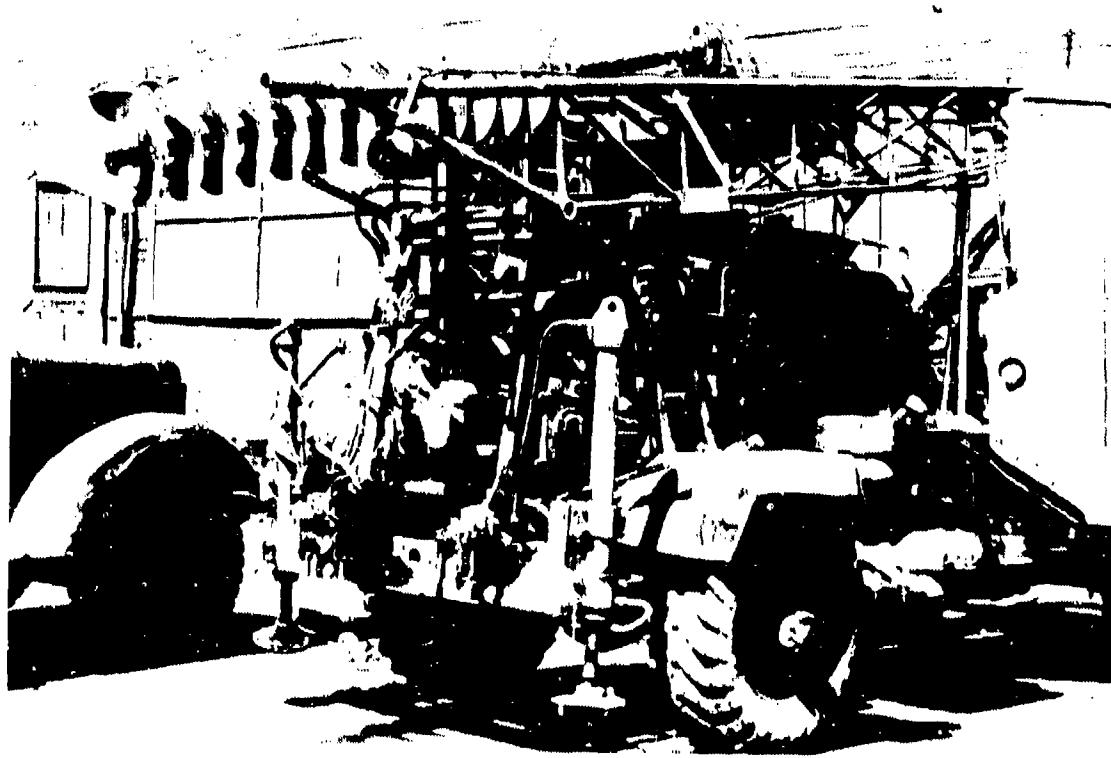


Figure A12. Drill rig and construction auger used in Siberia. In this case the entire bit is a spear point.